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Biological effects of cosmic radiation during stratospheric flights

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Abstract. Cosmic radiation is a field of renewed investigation and involves several scientific challenges. A great area of interest is represented by radiobiology, a strategic field of investigation in space-biomedicine. Despite the data collected until now, much more must be done in order to obtain an estimate of the hazard to man from cosmic rays. Stratospheric balloon-based experiments for adequate time intervals (20-100 days) at high altitude (30-40.000 mt) could constitute an excellent experimental model of exposition, providing reliable data and opportunity to study the biological response to cosmic rays and to determined the degree of radioprotection afforded by physical-pharmacological devices.

Key words. Stratospheric balloons - radiobiology - galactic cosmic rays

1. Introduction

The discovery of cosmic rays was originally connected with the question how ionization changes with altitude. In 1911 V. Hess completed several flights on balloon, carrying with him a Wulf electrometer (Hess and Eugster 1949; Hess 1912). Greater ionization was revealed at height rather than at ground level. This led Hess (who received the Nobel price in 1936) to suspect the existence of a “special” radiation harder than γ-irradiation and of “extraterrestrial” origin. The radiation was originally called Höhenstrahlung, meaning “high altitude radiation”. In 1923 Millikan and Otis (Millikan and Cameron 1928), in measuring the absorption coefficient of cosmic rays in lead on the summit of Pike’s Peak, came to the conclusion that this value was of the same magnitude as that for γ-rays, meanwhile the coefficient of absorption was ten times less than for γ-rays in water at a depth up to 10 m (Skobelzyn 1927).

At the time, there were no particle accelerators or nuclear reactors, and scientists believed “cosmic rays” offered the key to unlocking the secrets of the atom and promised a new source of power. The problem was the atmosphere absorbed much of this radiation, so studying it required flying to great heights, into the layer of the atmosphere called the “stratosphere”. As it turned out, balloons were the best vehicles for ascending to the stratosphere where cosmic radiation could be studied.

Auguste Piccard of the University of Brussels was the first person to use a sealed capsule for high altitude flight. Piccard was also interested in studying cosmic radiation. On May 27, 1931, he and his assistant Paul

Kipfer reached an altitude of 52,777 feet. For the flight, Piccard designed a spherical aluminium capsule. Piccard named his balloon “FNRS”, after the Belgian “Fonds National de la Recherche Scientifique” (National Scientific Research Fund), which sponsored his flight. Piccard chose a sphere because it provided the greatest volume relative to its size; aluminium because of its light weight. Piccard pressurized his capsule to maintain a sea-level atmosphere. He studied the oxygen systems used on submarines and incorporated a modified “Dräeger” system built for U-boats. Beds of soda lime in the Dräeger apparatus absorbed carbon dioxide in the cabin atmosphere. Liquid oxygen was allowed to vaporize at a controlled rate to compensate for what was consumed. The system processed about 20 gallons of air per minute. For thermal control, Piccard painted one side of the sphere black, the other white. A fan mounted on a pole would let him rotate the capsule to achieve the desired cabin temperature. Piccard, who completed flights to the stratosphere in a balloon in 1931-1932 for the first time, fully recognized the existence of biologic effects due to cosmic rays (Piccard 1933, 1954). Previously, Skobelzyn (Skobelzyn 1927) proved experimentally by the use of Wilson cloud chambers, that cosmic radiation contains charged particles of extremely high energy. Subsequently, in 1947, Feier made the very important discovery that nuclear particles with mass number up to 40 and with energies of several billion electron volts are continually penetrating the Earth’s atmosphere (Freier et al. 1948). In 1967 Fowler further evidenced the existence of super heavy particles, with an atomic number up to and perhaps beyond that of uranium (Z=92) located within cosmic rays (Fowler et al. 1967).

After World War II, interest in high altitude balloon research again surfaced. In the 1950s there were several important scientific experiments and findings in the areas of cosmic radiation, ozone concentrations, carbon dioxide, radioactive dust rallied from aboveground nuclear testing, long-range weather forecasting, and many others. Manned high altitude balloon flights resumed. The ManHigh I Program flights were designed to test high altitude escape equipment and procedures that would be used in the new generations of high-altitude airplanes. In the ManHigh II Program, experiments were conducted to investigate the near space environment and Its effects on humans in preparation for spaceflight. So, what was the impact of manned high altitude balloons on space flight? Fifteen flights to the edge of space between 1931 and 1961 demonstrated the reliability of cabin life support systems. Overall, the systems performed as planned. The closest to a life support system failure occurred during the first Manhigh flight when the oxygen pressure controller was installed incorrectly.

2. Manned and unmanned balloon fights

Physical and psychological screening procedures used for America’s space pilots were first used to select the Manhigh III pilot. Medical personnel who supported Manhigh and Strato-Lab also supported Project Mercury. Finally, and perhaps most importantly, there was the knowledge that it was possible to build a sealed cabin with a life support system that could sustain one or more individuals in an alien, inhospitable environment. This knowledge helped pave the way for subsequent space flights. The Strato-Lab Program was designed to conduct aeromedical research on flight crews, astrophysical investigations, and geophysical observations. In addition, studies of air pollutants and spectrographic and photographic studies of the Sun and Venus were conducted. By 1970, there were over 500 yearly scientific high altitude manned and unmanned balloon launches in the United States. These flights were used to study aeronomy, solar physics, astronomy, magnetic fields, cosmic dust, biology, and other areas of scientific interest. A specific investigation on radiation effects on biological samples was made with a stratospheric balloon during the program ODISSEA in 1987 lauched from Trapani-Milo (Sicily, Italy) and recovered over Spain after a 24 hours flight. The results were quite inconclusive, conversely to the large success of the astrophysical experiments carried out from the Trapani Facility for almost 20 years (Ubertini, this proceedings).

The crew of a spacecraft is exposed to both primary and secondary cosmic radiation: while the walls of a spacecraft stop most primary galactic cosmic radiation (GCR) particles, some can penetrate the wall material. The resulting interactions yield secondary particles of the same nature but weaker in energy, as well as neutrons and X-rays. On the ground, while certain protons do reach the surface of Earth, most of the GCR is stopped by the atmosphere: α particles and heavy ions practically disappear at an altitude of 20,000 m, but high atomic number-high energy particle component (HZE) can penetrate deeper. All of these particles collide with the oxygen and nitrogen atoms of the atmosphere. The resulting interactions give rise to electromagnetic radiation (γ-rays), neutrons, mesons, electrons etc. Among GCR particles, HZE particles are of utmost interest.

The radiation from HZE particles was discovered in 1948 and radiobiologists soon became concerned as to the effect this new type of ionizing radiation might have upon living systems exposed to it. Soon after discovery of the high atomic number-high energy particle component (HZE), Tobias in 1952 predicted that a visual light flash sensation could be experienced by individuals exposed to these particles. There followed direct experimental evidence of the character and effectiveness of HZE particles. Chase (1954) describes greying of hair in balloon-borne black mice; Eugster (1955) demonstrated cellular death by single hits of heavy ions on Artemia Salina eggs; and similar effects were reported by Brustad (1961) on maize embryos. Brain injury studies were attempted by Yagoda and co-workers (1963) and by Haymaker and co-workers (1970) in balloon-borne mice and monkeys, respectively.

Very high local concentration of absorbed energy produced by an HZE particle can cause serious biological effects upon an organism since complete cells can be damaged or destroyed. The ultimate consequence of such damage is dependent upon the organism's ability to repair or replace the affected cell. The destruction of cells in the central nervous system is of serious concern since these cells cannot regenerate.

Although the potential hazards to living systems from the heavy nuclei component of galactic cosmic radiation was recognized, very little active research was conducted until the crews of Apollo 11 and subsequent Apollo missions reported experiencing a visual light flash phenomenon. The primary reason for the inactivity in this field was an inability to generate particles with comparable charge and energy with existing accelerators. The light flashes experienced by the astronauts provided an increased impetus for radiobiological experimentation by direct exposure to the HZE particles in space. Exposure to HZE particles during a spaceflight mission offers several unique advantages, principally, exposure to the primary spectra modified only by the interactions in the relatively lightly shielded space vehicle. The Biostack experiment was specifically designed to study the effect of individual heavy nuclei of the cosmic radiation environment upon biological systems during actual space flight. Since there were no means by which the Biostack experiment could be insulated from other spaceflight factors, such as null gravity, the experiment must be considered one of studying the combined effects of cosmic radiation and other spaceflight factors. The objectives of the Biostack experiments were to study, in a direct manner, the biological effects of individual heavy nuclei with high energy loss (HZE); to obtain as much information as possible on the mechanisms of biological damage by HZE particles; to measure the charge and energy spectra of cosmic radiation within the Apollo Command Module; and to provide data to allow an estimate of the hazard to man from space radiation.

3. Radiobiology on high altitude balloons

However, despite the impressive amount of research performed until now, much more should and must be done. Spatial Agency Reports "gives estimates of the uncertainty in the health (carcinogenic, mutagenic) risks from HZE particles. The reason is that there is only ground-based carcinogenesis experiment on cancer induction in animals". Furthermore "quantitative designs of appropriate countermeasures, such as shielding, and biological or biochemical schemes to reduce the damage from HZE particles are very rudimentary". The NASA Strategy Report "recommended a comprehensive research program to determine the risks from different types and energies of HZE particles and from high-energy protons for a number of biological end points". NASA's Strategic Program Plan is very clear in pointing out that "current knowledge of radiation effects in space is not adequate for the design of long-duration missions without incurring either unacceptable risks or excessive costs". On the other hand, due to its extensive energy spectrum and heterogeneous composition, ground-based accelerators can only generate radiation of a fixed nature and energy; this difficulty is enhanced as cosmic radiation and weightlessness may have combined effects. Simulation of these two factors is currently impossible technologically.

It is a matter of investigation if balloon-borne exposures were limited to a spectrum significantly modified by the shielding of the remaining atmosphere and by the geomagnetic field and more compelling evidence is needed in order to verify if balloon-exposure could be considered as a reliable model. The major facility for these experiments is the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory but it is available for only two to four weeks per year. At the present rate of progress it would take 20 or more years to complete the high-priority experiments recommended in the NASA's Strategy Report.

It should be outlined that balloons, reaching 15,000-40,000 mt, have long offered a cheap alternative to rocketry. Even if by their nature they cannot rise above the atmosphere, they can still rise above 99% of it, leaving dust, weather and water behind. From several points of view, high atmospheric layer can be considered as "space equivalent", according to the Strughold's concept of "space equivalence" (Tonias and Grigor'yev 1975). He realized there is no definite demarcation where the atmosphere ends and space begins; rather, as altitude increases, there are gradations where an unprotected body experiences different physical effects. One of these occurs around at 50,000 feet, where atmospheric pressure equals the pressure of water vapour and carbon dioxide in the lungs. With regard to respiration, a person at this altitude would be in the functional equivalent of outer space. To survive beyond this altitude, oxygen must be provided under pressure. The next demarcation occurs at 63,000 feet, where water boils at 98.6° Fahrenheit. Above this point, bodily fluids would begin to vaporize, so some sort of pressurized garment or sealed capsule must be used. The significance of Strughold's observation was that, from the effect on the human body, the functional equivalent of outer space begins at altitudes of only 17-20,000 mt.

More important, both instruments, biological specimens or humans are exposed during balloon's flights to several kinds of charged particles that cover about 90-97% of the galactic cosmic radiation. The relative dose at flight altitudes (20-40 Km) mainly originates from neutrons, electrons, photons, with a smaller proton component, whereas myons and a small fraction of neutrons mainly contribute to the dose on the ground level (Fig. 1) (PTB web site 2005).

The earth's atmosphere is bombarded by high-energy particles from our galaxy (primary cosmic radiation). In the upper atmospheric layers, these particles react with air molecules. As a result of nuclear reactions, a great number of secondary particles (secondary cosmic radiation) is formed. Some of these secondary particles decay again, are absorbed in the atmosphere or possibly penetrate into the earth. The radiation fluency generated in this way is subdivided into three main components: electrons/photons, hadrons (nuclear components) and myons (heavy electrons).

It is well-known that the amount of radiation exposure due to cosmic radiation at a specific place depends, above all, on the flight altitude, the magnetic latitude and the solar cycle. Close to the pole, it is from two to ten times as high as close to the equator. Moreover, launching from Polar Regions offers several advantages: launching during the polar day allows the payload to stay in the sunlight for months; this solves the most part of energy and

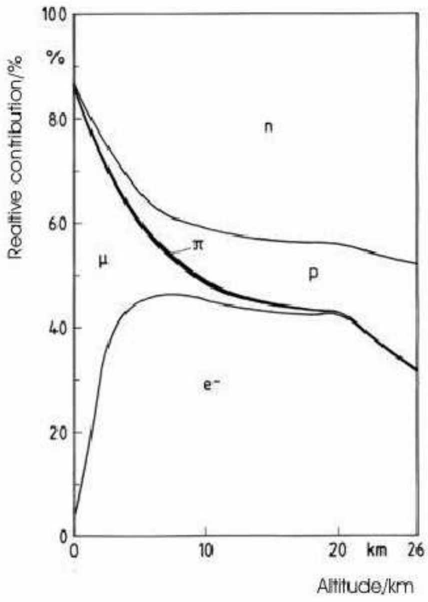

Fig. 1. Composition of GCR in respect to altitude.

temperature problems, extremely important for long experiments, and offers an easy way to orientate the payload. Moreover, the circumpolar stratospheric winds bring the balloon in a circular predictable trajectory making easy its recovery. This localized trajectory can be of great interest for polar sciences, for cosmology and astronomy (instruments can integrate for days the same portion of sky), for earth sciences. The trajectory itself is an object of investigation for atmosphere scientists. Launching Stratospheric Balloons from polar area is a usual activity in the southern hemisphere, but quite new for the northern one. Big Long Duration Balloons (LDB up to 3 weeks of operation) with a weight of over two tons, have been successfully operated from McMurdo (USA, Antarctica), getting impressive results, like for example BOOMERanG, defined by NASA one of the top ten results during the last 20 years (De Bernardis et al., 2000; Masi et al., 2006). Pegaso was the first LDB experiment carried out in the northern hemisphere, to be launched from Svalbard Islands, and it made for the first time the circumnavigation of the north pole. Even with a conventional "open balloon" one can achieve a time at float as long as several weeks. There is a lot of technological development going on in this field, with the so called "superpressure balloons", in order to achieve even longer time at float.The new 120-metre-diameter balloons will make possible long duration experiments in biological fields, enabling studies and performances until now never reached. This balloon should fly for about 100 days (with relative costs) at an altitude of 40.000 mt, and above, if and when possible. Unlike the conventional balloons, the new balloons are sealed to keep the helium at high pressure and their volume constant.

These characteristics made stratospheric balloons potentially excellent as models for studying cosmic radiation impact on biological specimens. In 2004, a stratospheric balloon of NASA was launched from the Antarctica's McMurdo base. The balloon raised the CREAM (Cosmic Ray Energetics And Mass) experiment up to 40 kilometres high. In the experiment, coordinated by Eun Suk Seo of Maryland University, participate American universities (Maryland, Chicago, Penn State, Ohio), South Korea universities (Ewa, KyungPook) and an Italian group of Pisa, Siena, and Torino departments of the Italian Institute for Nuclear Physics (Infn), directed by Pier Simone Marrocchesi. The balloon, following circulation of high winds, sailed around the ice continent for about three weeks. During this time, data of great scientific interest have been gathered, concerning flows of charged particles of highest energy (cosmic rays) coming from Space. The CREAM experiment was conceived in particular to investigate the origin of cosmic rays and their acceleration mechanisms: two questions that are still waiting for a definite answer, in spite of the enormous advancements carried out in this field since the discovery of cosmic rays in 1912.

4. Conclusions

It is tempting to speculate that a balloon-based experiment - for adequate time intervals (30-

100 days) could provide reliable information about radiobiological effects due to cosmic rays, keeping in mind the following priorities: a) assessing the carcinogenic risk; evaluate the effects of GCR on central nervous system; how to extrapolate experimental data from cells or rodents to humans. Moreover is critical to evaluate the effects of chronic exposure to GCR on fertility and cataract formation, to determine whether drugs could be used to protect against the effects of radiation exposure; and finally to assess whether biological response to GCR depend only on the Linear Energy Transfer (LET) or on the values of the atomic number and energy separately.

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